Low-Temperature Emission Control to Enable Fuel-Efficient Engine Commercialization

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Acknowledgments

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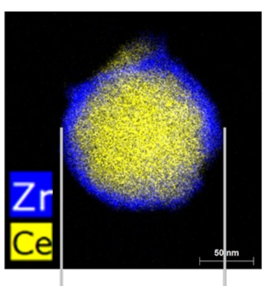
  – Ken Howden, Gurpreet Singh, Mike Weismiller
- **Contributions from the ORNL Team:**
  – Michelle Kidder, Pranaw Kunal, and Michael Lance
- **Collaboration with University At Buffalo:**
  – Judy Liu, Junjie Chen, Prof. Eleni Kyriakidou



- **Access to instrumentation at ORNL:**
  – Micrographs and elemental maps captured using instrumentation (FEI Talos F200X S/TEM) provided by the Department of Energy, Office of Nuclear Energy, Fuel Cycle R&D Program and the Nuclear Science User Facilities

Project Overview

Timeline

- Year 1 of 3-year program

  Project start date: FY2019

  Project end date: FY2021

- Builds on previous R&D in FY16-FY18

Budget

- FY19: $500k (Task 1*)

*Task 1: Low Temperature Emissions Control Catalysis Research

Part of large ORNL project "Controlling Emissions from High Efficiency Combustion Systems" (2018 VTO AOP Lab Call)

Barriers Addressed

U.S. DRIVE Advanced Combustion & Emission Control 2018 Roadmap Barriers & Targets:

- Addressing emission compliance barrier to market for advanced fuel-efficient engine technologies, such as 90% conversion of NOx, CO and HC at 150°C
- Efficiency, durability, sulfur tolerance of aftertreatment systems

Collaborators & Partners

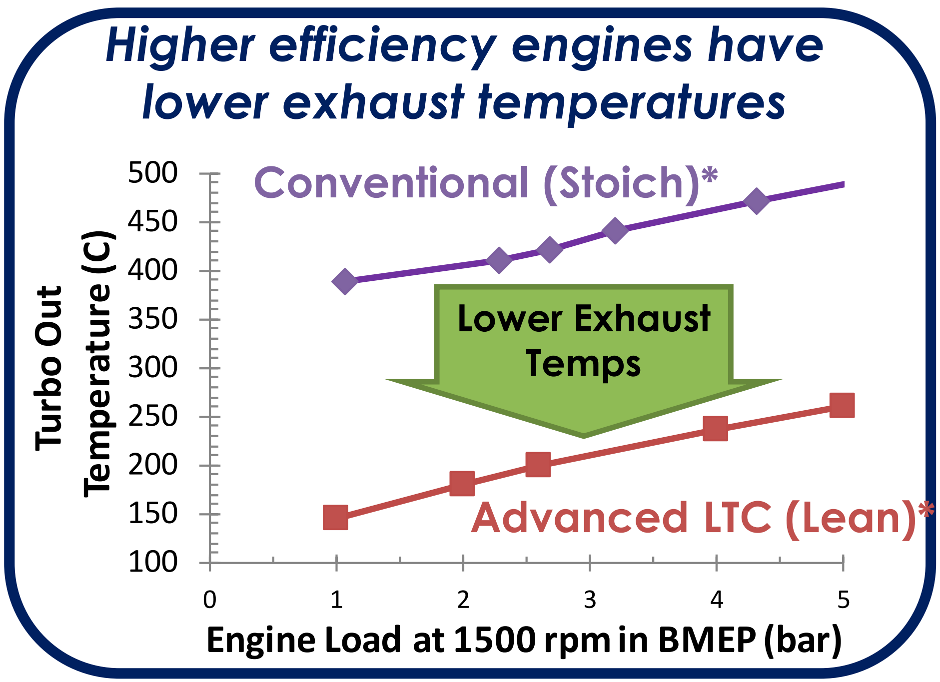
- US DRIVE Advanced Combustion and Emission Control Tech Team
- University at Buffalo (SUNY)

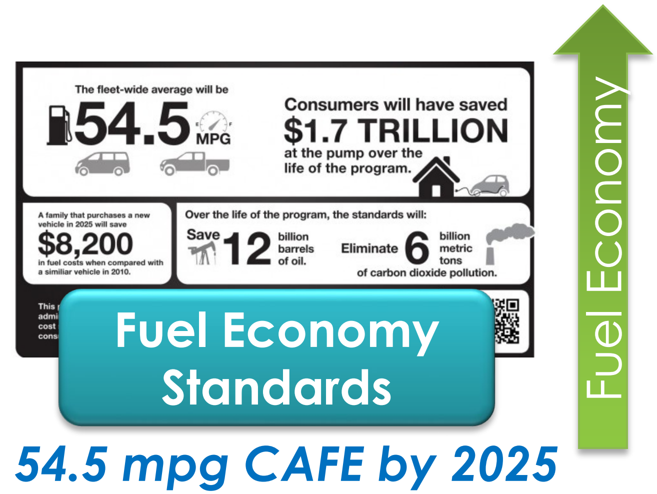
Objectives and Relevance

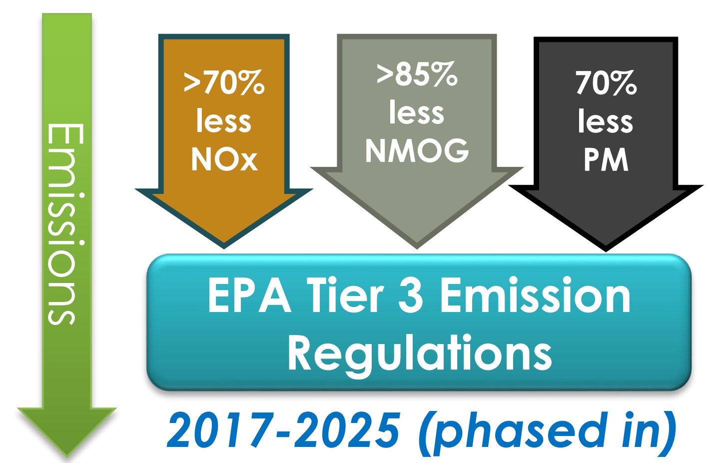
Develop new emission control technologies to enable fuel-efficient engines with low exhaust temperatures (<150°C) to meet emission regulations

Goal: 90% Conversion at 150°C

- Greater efficiency lowers exhaust temperature
- Catalysis is challenging at low temperatures
- Emissions standards getting more stringent







* "**Conventional**": modern state-of-the-art GDI Turbocharged (stoichiometric)
* "**Advanced LTC**": advanced lean-burn Low Temperature Combustion (LTC) engine

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Relevance: Guiding Documents Define Industry Needs

USDRIVE A
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Identified Needs Addressed:

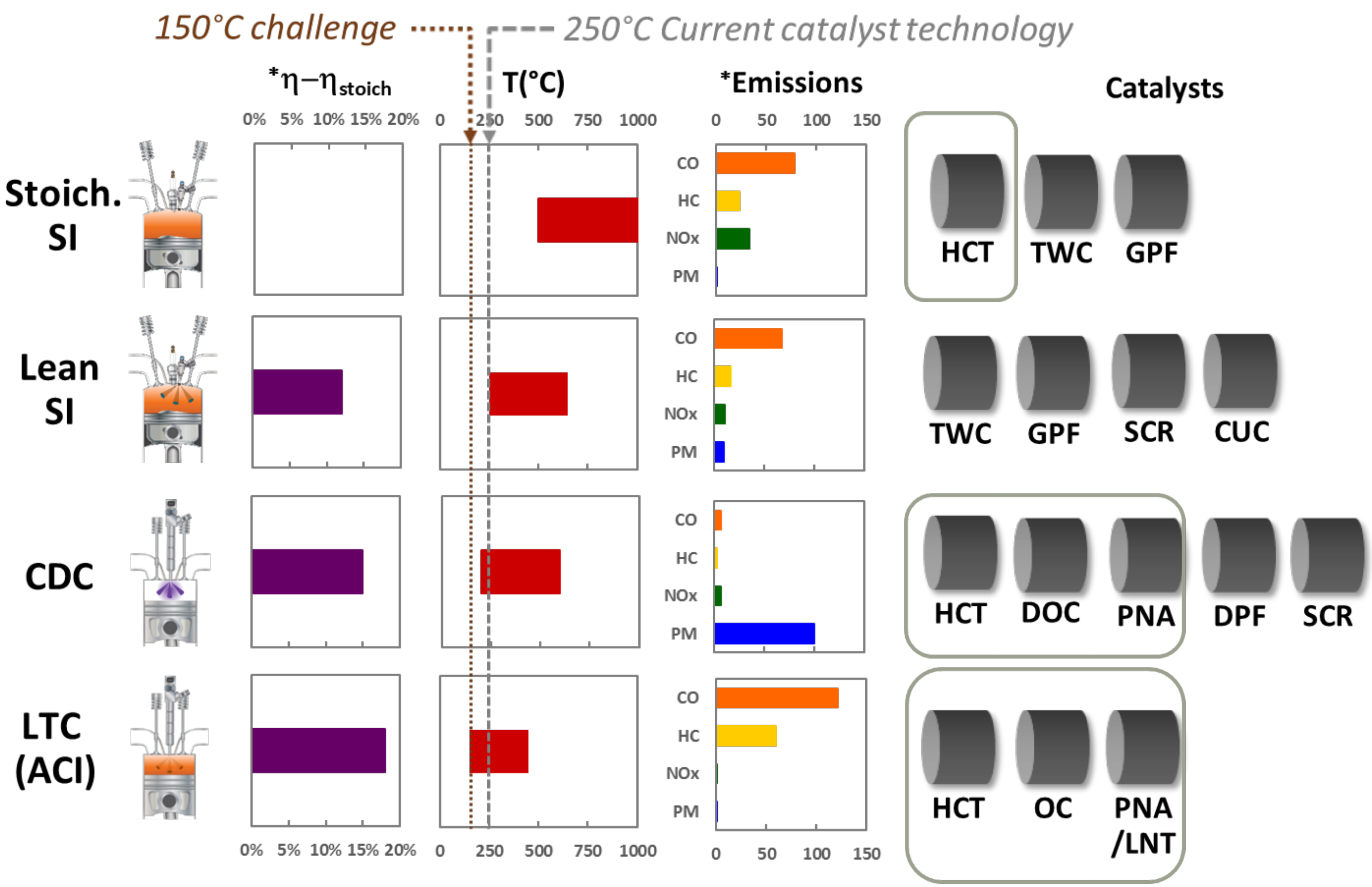
- Lower temperature CO and HC oxidation
- Low temperature NOx reduction
- Cold start emission trapping technologies
  - Especially passive NOx adsorbers
- Reduced PGM
- Better durability
- Promote innovative catalytic solutions via partnering with DOE BES programs

Low Temperature Combustion (LTC)

Dilute Gasoline Combustion

Clean Diesel Combustion (CDC)

Approach: Lean low-temperature exhaust creates emissions challenges that must be addressed



Low Temperature Emissions Control
Discover new low T catalysts & traps

CLEERS
Model new trap materials

Lean Gasoline Emissions Control
Develop emissions pathway for lean gasoline engines to meet emissions

Chemistry and Control of Cold Start Emissions
exhaust chemistry impact on functionality

TWC: three-way catalyst
HCT: hydrocarbon trap
PF: particulate filter

SCR: selective catalytic NOx reduction
CUC: CO/HC clean-up catalyst
OC: oxidation catalyst

PNA: passive NOx adsorber
LNT: lean NOx trap
***** – semi-quantitative representation

Employ low temperature protocols to evaluate catalysts

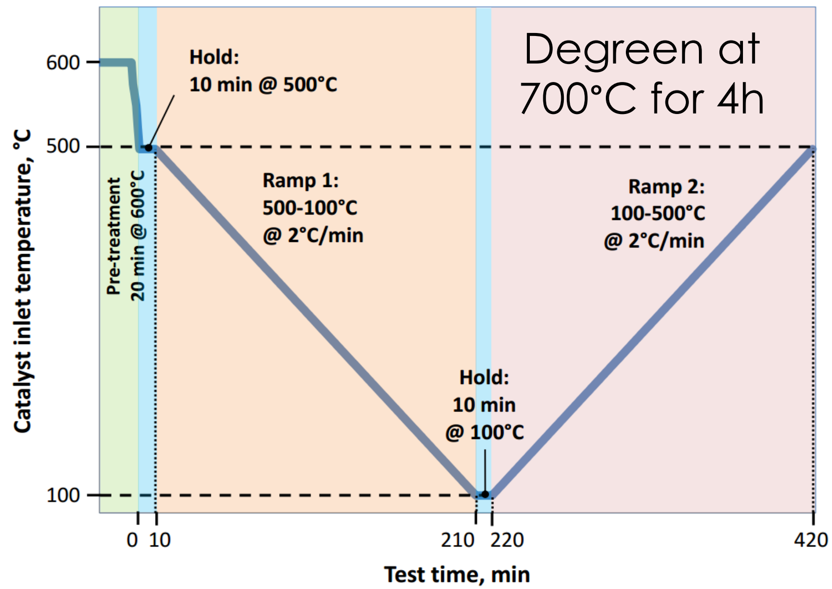
- Project employs US DRIVE Advanced Combustion and Emission Control Team Aftertreatment Protocols for Catalyst Characterization and Performance Evaluation
- Full protocol at: www.CLEERS.org

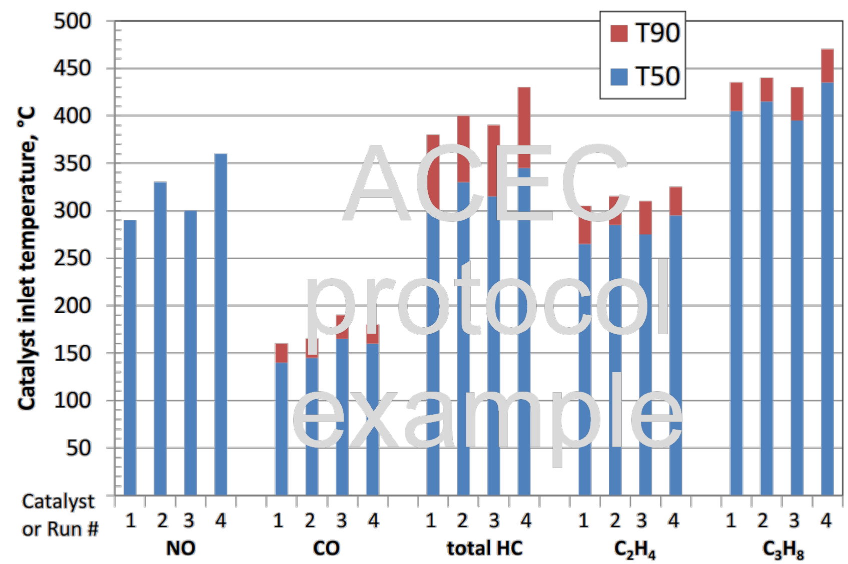
LTC-D: Low Temp. Combustion Diesel

Total HC_1:	3000 ppm
C_2H_4:	500 ppm
C_3H_6:	300 ppm
C_3H_8:	100 ppm
***$C_{12}H_{26}$:**	**2100 ppm**
CO:	2000 ppm
NO:	100 ppm
H_2:	400 ppm
H_2O:	6 %
CO_2:	6 %
O_2:	12 %
Balance N_2	

Powder Catalyst Requirements

- Reactor ID 3-13 mm
- Catalyst particle size ≤ 0.25 mm
- Catalyst bed L/D≥1
- Space velocity
  - 200-400 L/g-hr
  - For 0.1 g, flow 333-666 sccm





* - we employed decane ($C_{10}H_{22}$) due to bubbler needs

Collaborations

- **Academia**
  - **University at Buffalo (SUNY):** Prof. Eleni Kyriakidou, Judy Liu, Junjie Chen
    - Catalyst synthesis, characterization, and evaluation
  - **Harvard University:** Wyss Institute for Biologically Inspired Engineering, Prof. Joanna Aizenberg
    - Evaluation of new types structured/stable catalysts (PGM supported on metal oxides)
  - **Karlsruhe Institute of Technology:** joint paper on oxidation catalysts with Olaf Deutschmann
- **Industry**
  - **USCAR/USDRIVE Low Temperature Aftertreatment (LTAT) working group**
    - low temperature evaluation protocols
  - **Johnson Matthey:** Industry input from Haiying Chen; partner on DOE project Sharan Sethuraman
- **DOE Basic Energy Science researchers**
  - Sheng Dai and Ashi Savara (ORNL), Center for Nanophase Materials Science
    - Catalysts synthesis and characterization
- **Other DOE funded projects**
  - **CLEERS:** Dissemination of data; presentation at CLEERS workshops
  - **PNNL:** bi-monthly teleconferences established to share data on VTO projects
  - **University of Houston-led project with University of Virginia, Johnson Matthey, Southwest Research Institute**
    - Project focusing on low temperature catalysis

Milestones of 3-year project

- FY19 Milestones: **_on track_**
  - Determine ion-exchange/nanoparticle distribution in HCT/PNA
- FY20 Milestones: **_on track_**
  - Determine which multifunctional configuration yields the highest activity while simulating cold start heating rates using the top performing HC Trap/PNA + DOC
- FY21 Milestones: **_on track_**
  - Demonstrate 90% conversion of criteria pollutants CO, HC, and NOx at 150°C on hydrothermally-aged catalysts

Technical Accomplishments

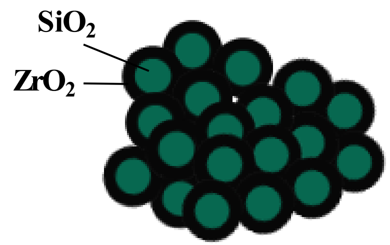
- Oxidation catalysts

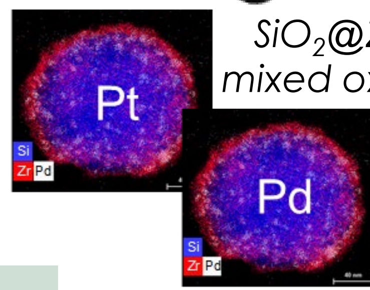
- Trap/Adsorber Materials
  - Hydrocarbon trap
  - Passive NOx adsorbers

- Combined systems

Results are building on promising $SiO_2@ZrO_2$ core@shell support for Pt and Pd catalysts

- PGM supported on a shell of ZrO_2 around a core of SiO_2 ($SiO_2@ZrO_2$)
- Exceptional low temperature activity observed with Pt+Pd physical mixture
  – Bed loading: 1.8% Pt and 1.0% Pd
  – Initially, aged at 800 °C for 10h



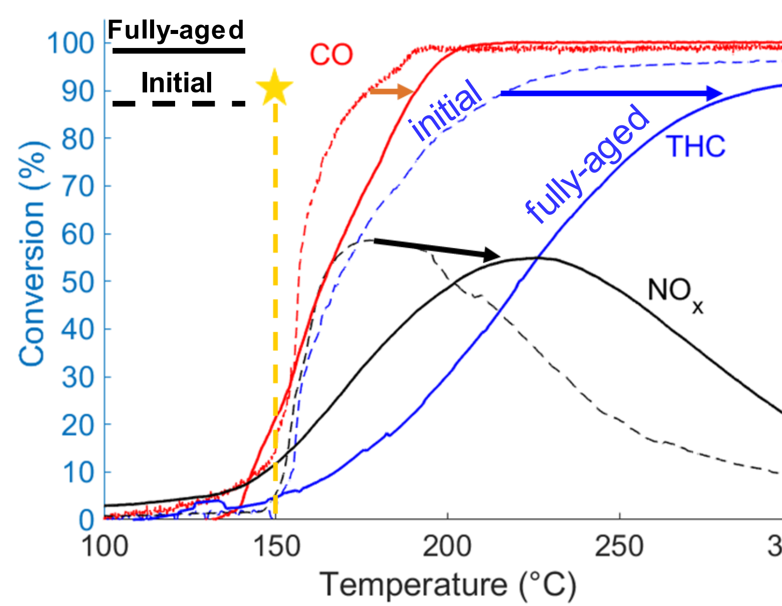


$SiO_2@ZrO_2$ mixed oxide

Conditions during 2ºC ramp	
total HC_1:	*3000 ppm*
C_2H_4:	*500 ppm*
C_3H_6:	*300 ppm*
C_3H_8:	*100 ppm*
$C_{10}H_{22}$:	*2100 ppm*
CO:	*2000 ppm*
NO:	*100 ppm*
Also H_2, O_2, H_2O and CO_2	

Protocol aging: reaction conditions at 800°C for 50h, 5 ppm SO_2 @ 300ºC 5 h

- Investigating improved durability of Pt and Pd on novel supports has been the focus of project
- Improving initial dispersion, and maintaining small Pt + Pd particle sizes throughout aging protocol



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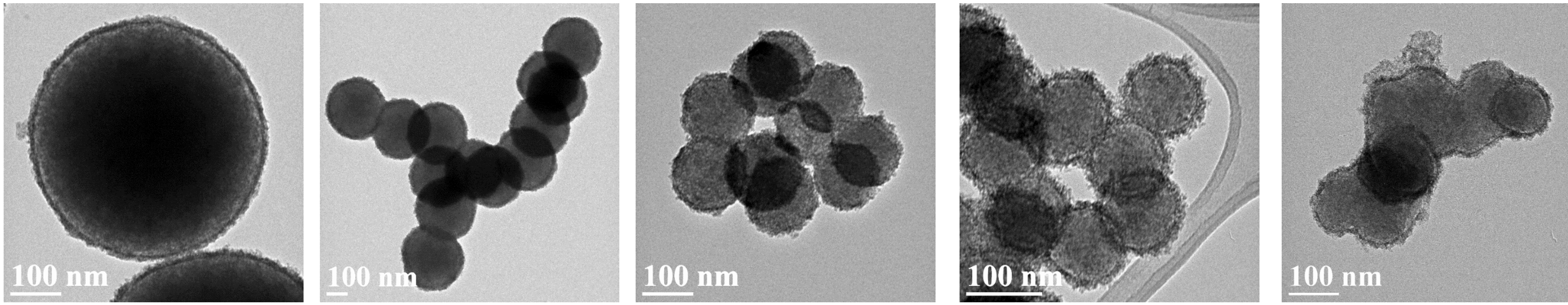
Varying diameter of SiO_2@ZrO_2 initiated with goal of creating surface that is less prone to Pt /Pd sintering



~490 nm | ~290 nm | ~150-200 nm | ~120 nm | <100 nm

- Loading Pd on smaller SiO_2@ZrO_2 spheres led to higher dispersion
  - Higher surface area may prevent Pd agglomeration
- Initially focusing on the 150-200 nm supports with Pd, Pt, and combinations
  - Evaluation of all supports forthcoming

SiO_2 size	> 450 nm	150-200 nm
Si@Zr BET SA	147 m^2/g	376 m^2/g
Si@Zr BJH PV	0.14 cm^3/g	0.33 cm^3/g
Pd dispersion*	3.9 %	24.1 %
Avg. Pd size*	28.8 nm	4.6 nm

* - based on CO chemisorption values and spherical particles size assumption

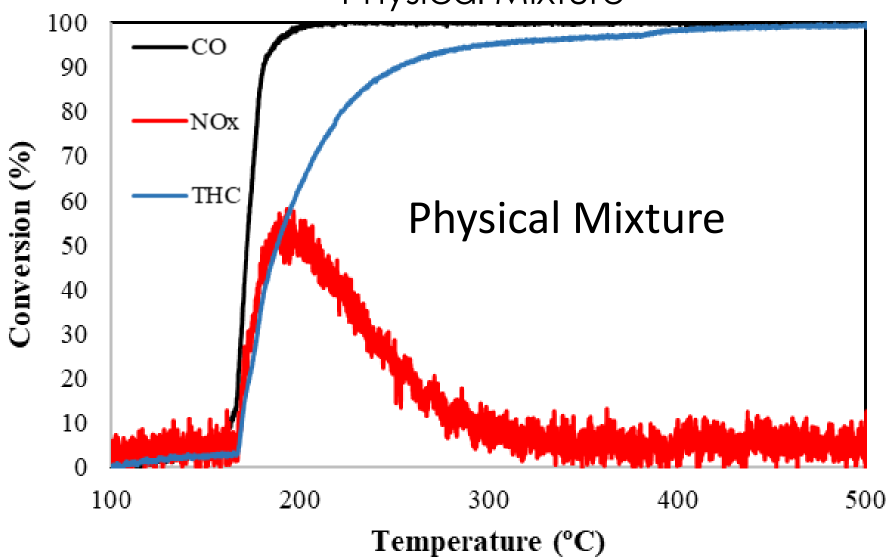
Combinations with Pd and Pt continue to show the best reactivity, but 150 °C goal is still elusive

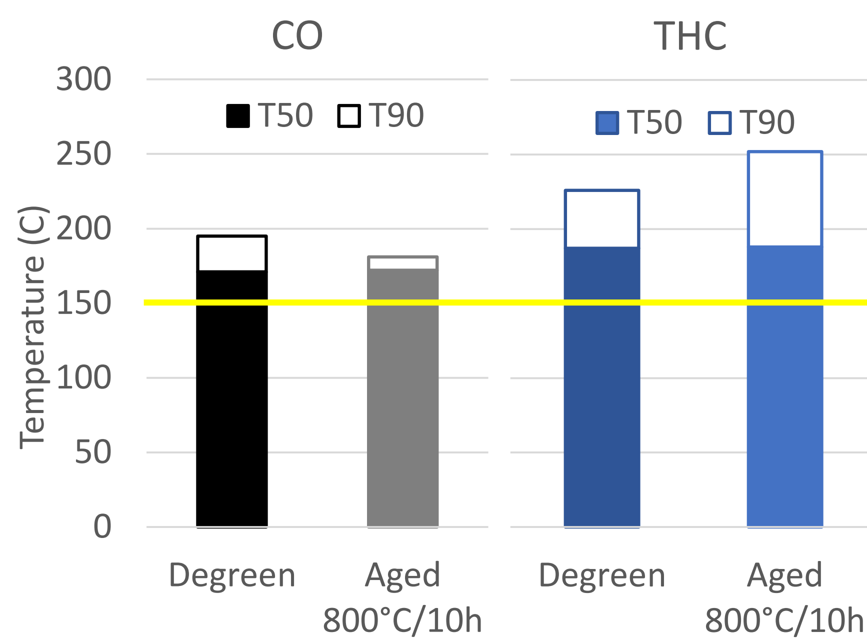
- Supports continue to show good initial THC reactivity, but not reaching 90% conversion until ~250 °C
- Other oxidation catalysts are under consideration

Conditions during 2ºC ramp

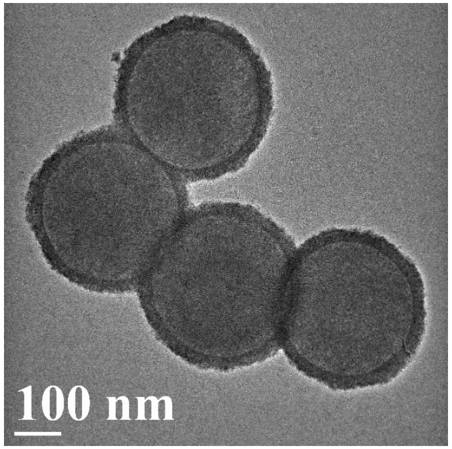
total HC_1: 3000 ppm
C_2H_4: 500 ppm
C_3H_6: 300 ppm
C_3H_8: 100 ppm
$C_{10}H_{22}$: 2100 ppm
CO: 2000 ppm
NO: 100 ppm
Also H_2, O_2, H_2O and CO_2

Hydrothermally aged at 800 °C for 10h
1% Pd/SiO_2@ZrO_2 + 1.8% Pt/SiO_2@ZrO_2
Physical Mixture



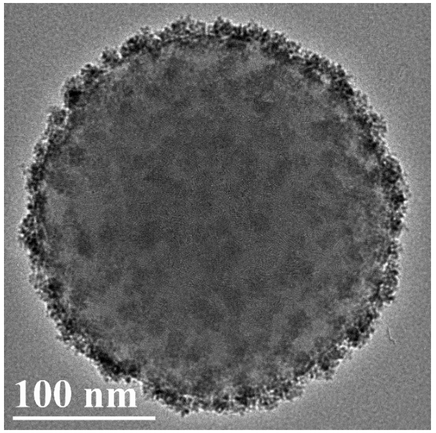


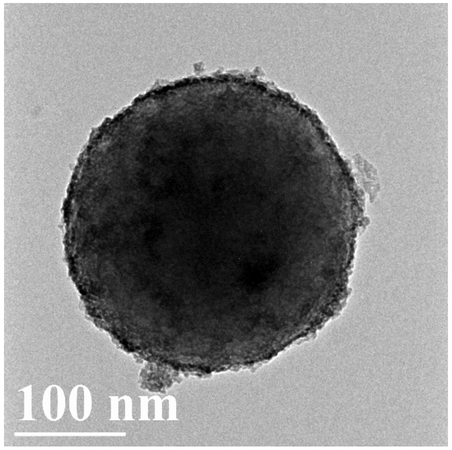
Other supports to be evaluated



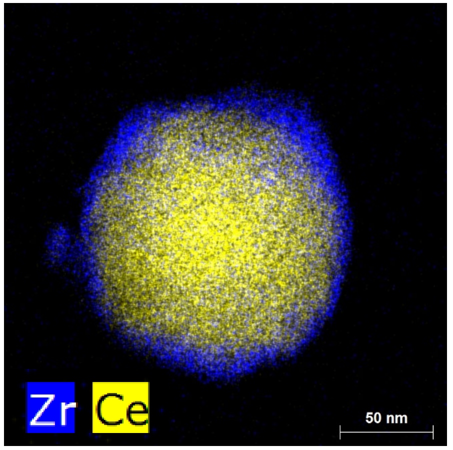
- $SiO_2@ZrO_2$ core@shell
  - Average diameter: 340 nm

- $SiO_2@CeO_2$ core@shell
  - Average diameter: 260 nm





- $SiO_2@CeO_2$-ZrO_2 core@shell
  - Average diameter: 260 nm



- $CeO_2@ZrO_2$ core@shell
  - Average diameter: 150 nm

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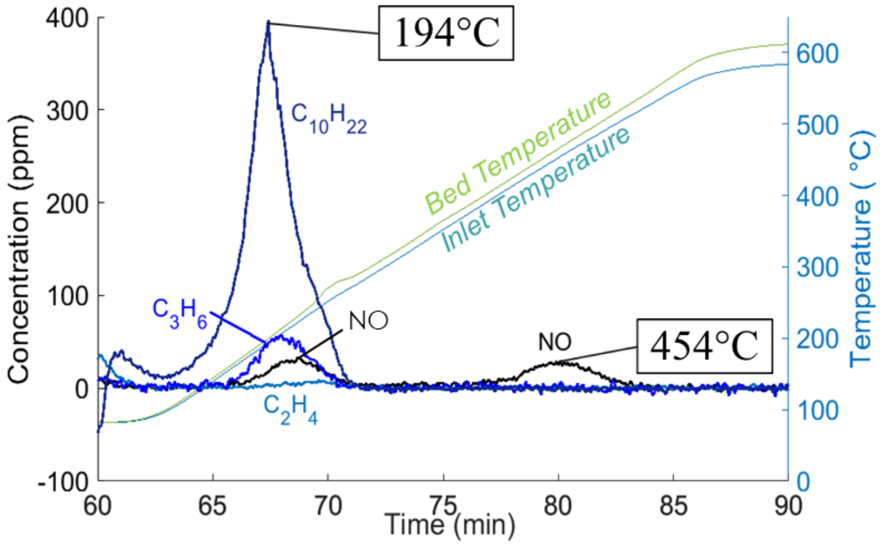
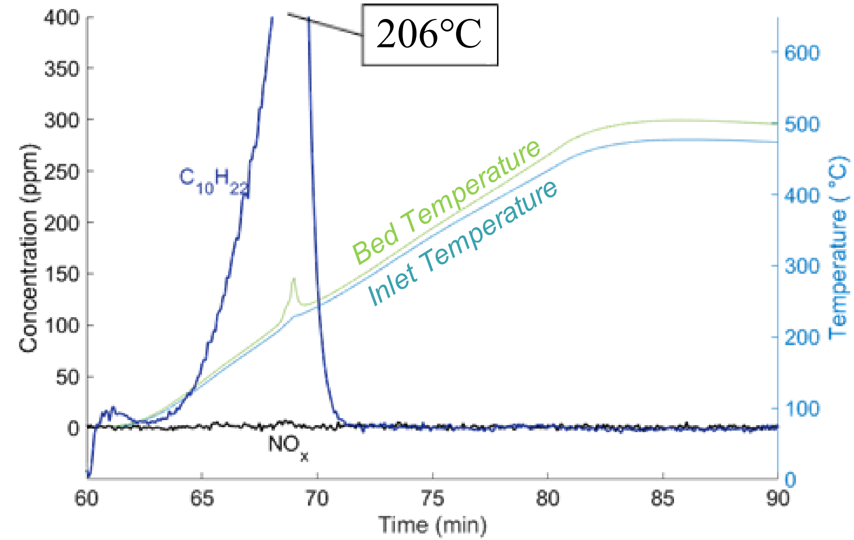
Technical Accomplishments

- Oxidation catalysts
- Trap/Adsorber Materials
  - Hydrocarbon trap
  - Passive NOx adsorbers
- Combined systems

Pd/ZSM-5 initially is a combination HC Trap and Passive NOx Adsorber, but loses NOx functionality with aging

Pd/ZSM-5 only: HC/NO release following 30 min storage





- Pd/ZSM-5 shows favorable release temperatures for pairing with an active DOC catalyst
- Release of NO across two peak temperatures
- Most functionality of Pd/ZSM-5 lost after aging;
  → However, decane is still trapped very effectively
- Indicates ion-exchanged Pd does not exist after aging
  – shown in literature to be essential for NO adsorption*

Conditions during 30 min storage step at 100°C

total HC_1:	*3000 ppm*
C_2H_4:	*500 ppm*
C_3H_6:	*300 ppm*
C_3H_8:	*100 ppm*
$C_{10}H_{22}$:	*2100 ppm*
CO:	*2000 ppm*
NO:	*100 ppm*

Also H_2, O_2, H_2O and CO_2

* - H.Y. Chen et al. Catal Lett 146 (2016) 1706. J. Lee et al. Catal. Sci. Technol. 9 (2019) 163.

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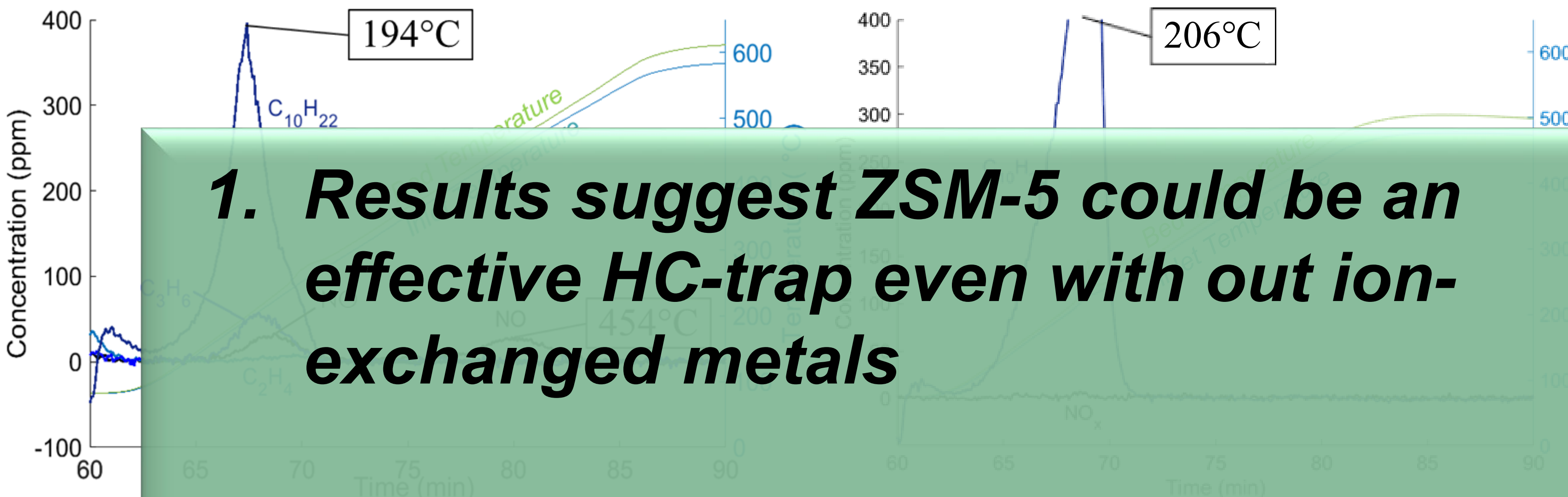

1. ***Results suggest ZSM-5 could be an effective HC-trap even with out ion-exchanged metals***

2. ***More durable zeolite needed to maintain NO adsorption functionality after 800°C***

- Pd/ZSM-5 sho... an active DOC catalyst
- Release of NO across two peak temperatures
- Most functionality of Pd/ZSM-5 lost after aging;
  → However, decane is still trapped very effectively
- Indicates ion-exchanged Pd does not exist after aging
  – shown in literature to be essential for NO adsorption*

Conditions ... storage step at 100°C

C_2H_4:	*500 ppm*
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Unexchanged ZSM-5 shows considerable HC storage; mostly heavy hydrocarbons

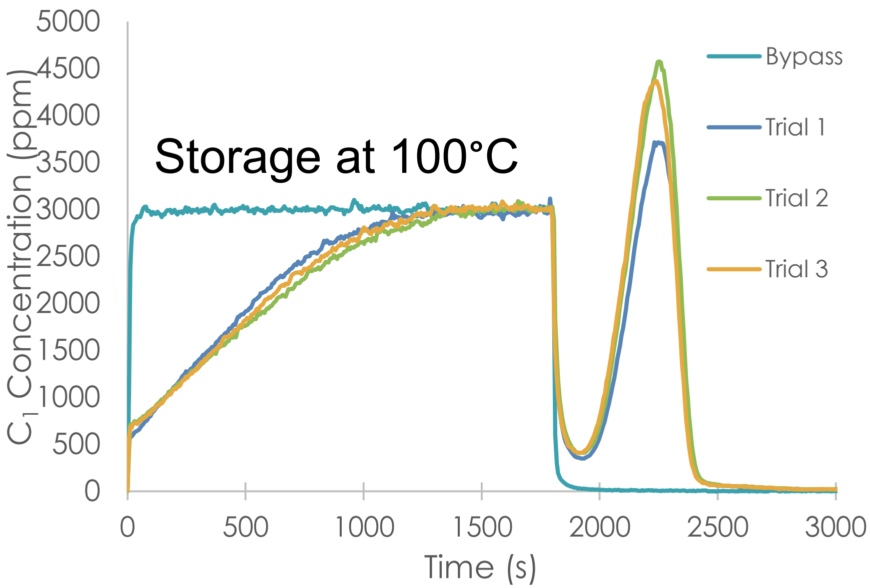
- Evaluation:
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h
- FID measurement indicates 2.5-3.0 mmols/g_{cat}
  - Measured during desorption
  - $C_{10}H_{22}$ comprises 88-93% of THC adsorption

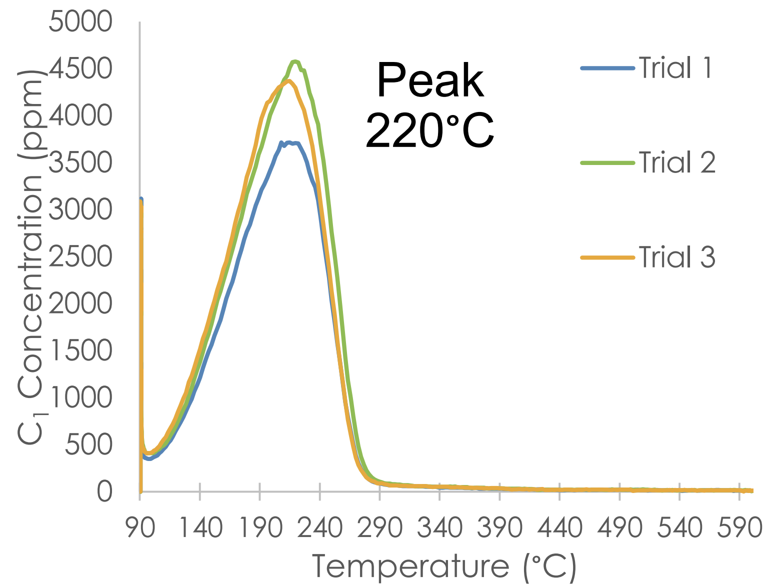
LTC-D oxidation protocol conditions during 30 min storage step at 100°C

total HC_1:	*3000 ppm*
C_2H_4:	*500 ppm*
C_3H_6:	*300 ppm*
C_3H_8:	*100 ppm*
$C_{10}H_{22}$:	*2100 ppm*
CO:	*2000 ppm*
NO:	*100 ppm*

Also H_2, O_2, H_2O and CO_2

Total Hydrocarbons: FID





Pd/SSZ-13 capable of storing significant NO under US-DRIVE protocol relevant conditions

- Synthesized 1% ion-exchanged Pd/SSZ-13 using commercially available SSZ-13 zeolite
- Evaluation:
  – 30 min at 100°C → 20°C/min ramp to 600°C → hold 1 h

LTC-D oxidation protocol conditions during 30 min storage step at 100°C

total HC_1:	*3000 ppm*
C_2H_4:	*500 ppm*
C_3H_6:	*300 ppm*
C_3H_8:	*100 ppm*
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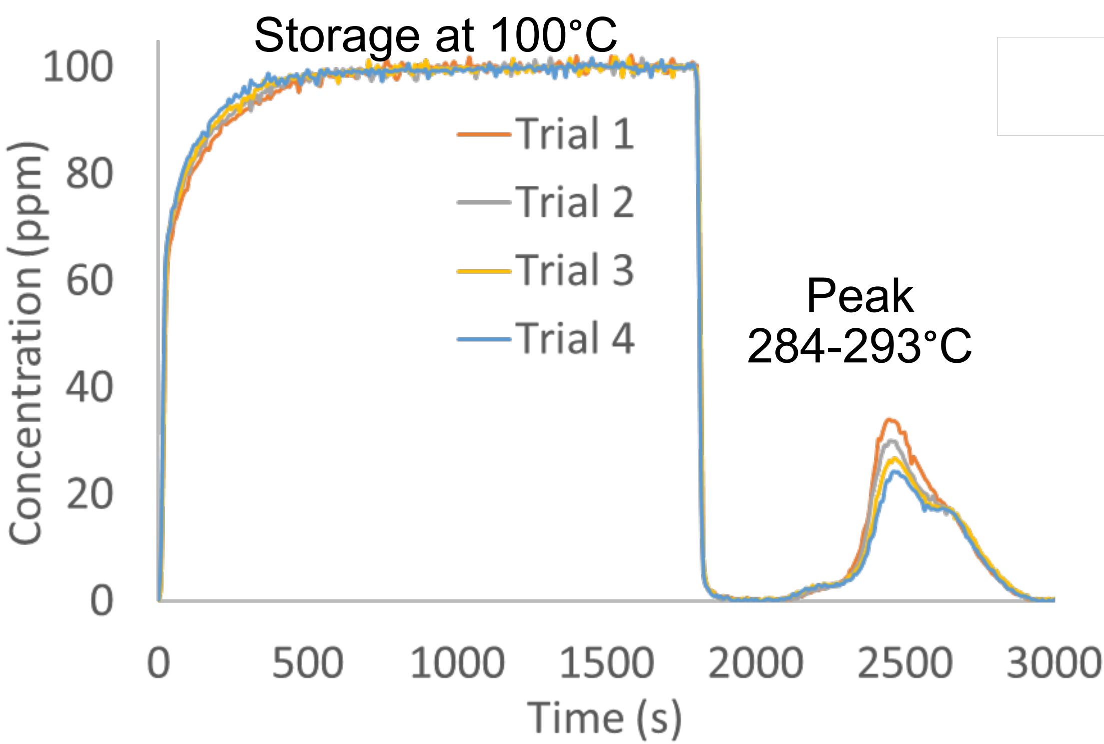

- NO:Pd decreases from 0.22 to 0.18 mol:mol
- Decreasing NO adsorption/desorption between trials
  1. Incomplete NO removal?
  2. Loss of Pd ion-exchange sites

Extending high temperature regen from 1h to 4h stabilizes NO storage capacity but losses still apparent

- Synthesized 1% ion-exchanged Pd/SSZ-13 using commercially available SSZ-13 zeolite
- Evaluation:
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h

LTC-D oxidation protocol conditions during 30 min storage step at 100°C

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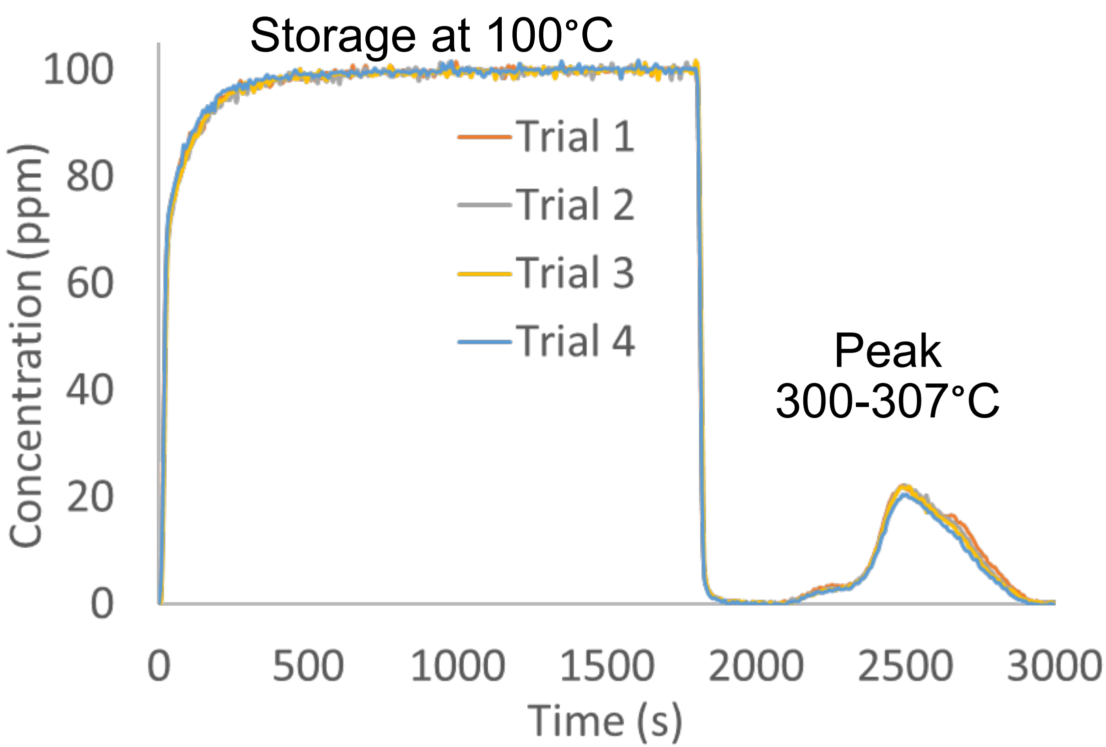

- NO:Pd stabilizes around 0.16 mol:mol
  - Lower than originally measured, 0.22-0.18
- Prefer higher uptake and Pd utilization

Aging Pd/SSZ-13 (US-DRIVE protocol) results in improved NOx uptake, suggesting incomplete initial ion-exchange

- Hydrothermal aging at 800 °C for 25h
- Evaluation:
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h

LTC-D oxidation protocol conditions during 30 min storage step at 100°C

total HC_1:	*3000 ppm*
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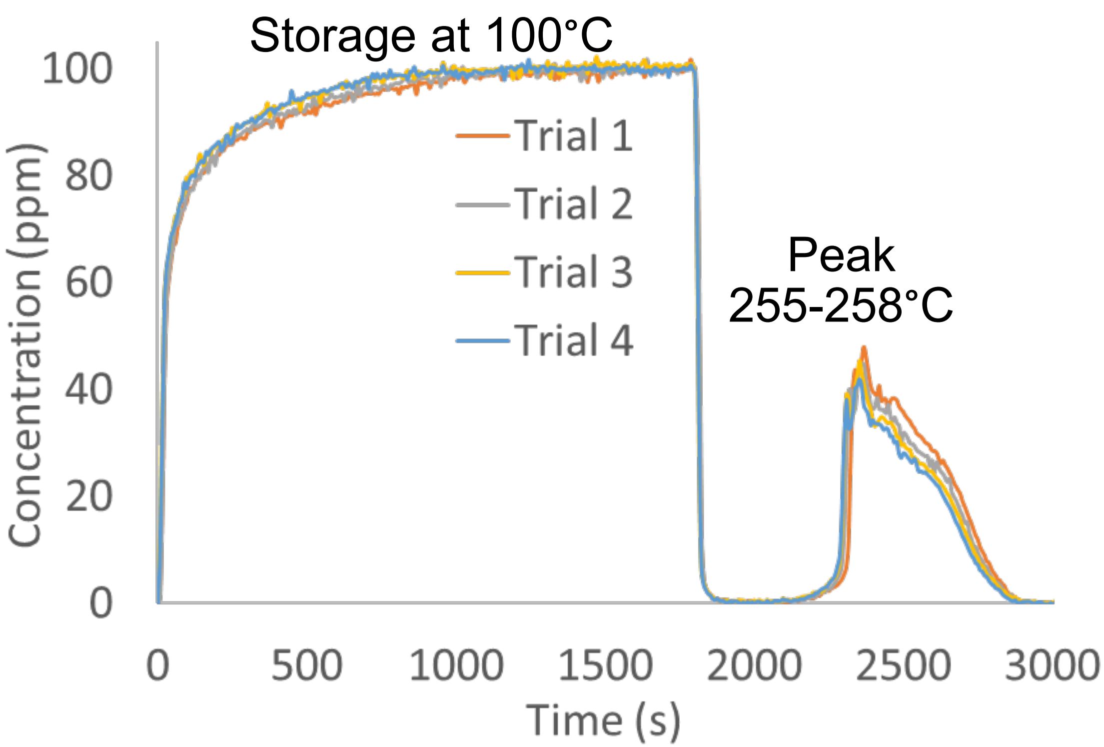
After aging for 25h at 800°C

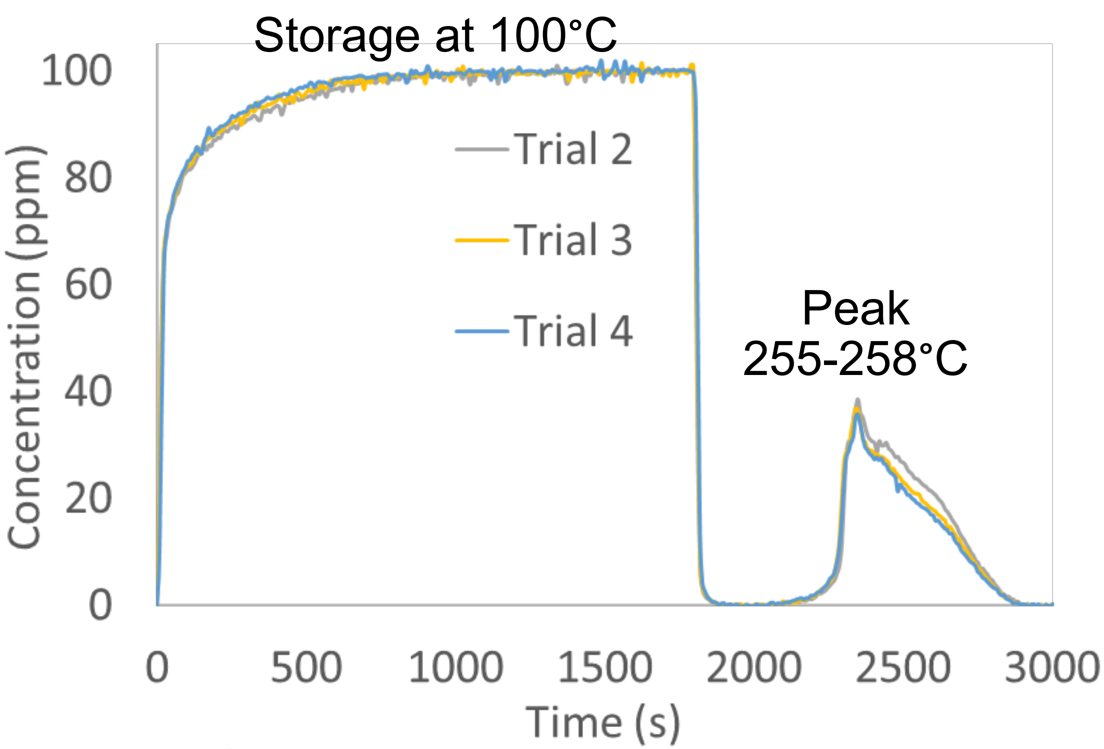


- NO:Pd increases to 0.3 mol:mol
  - Up from 0.16 mol:mol
- Still observing decreased adsorption with each trial
  - 0.32→0.30→0.28→0.27

Aging Pd/SSZ-13 (US-DRIVE protocol) results in improved NOx uptake, suggesting incomplete initial ion-exchange

- Hydrothermal aging at 800 °C for 50h
- Evaluation:
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h

After aging for <u>50h</u> at 800°C



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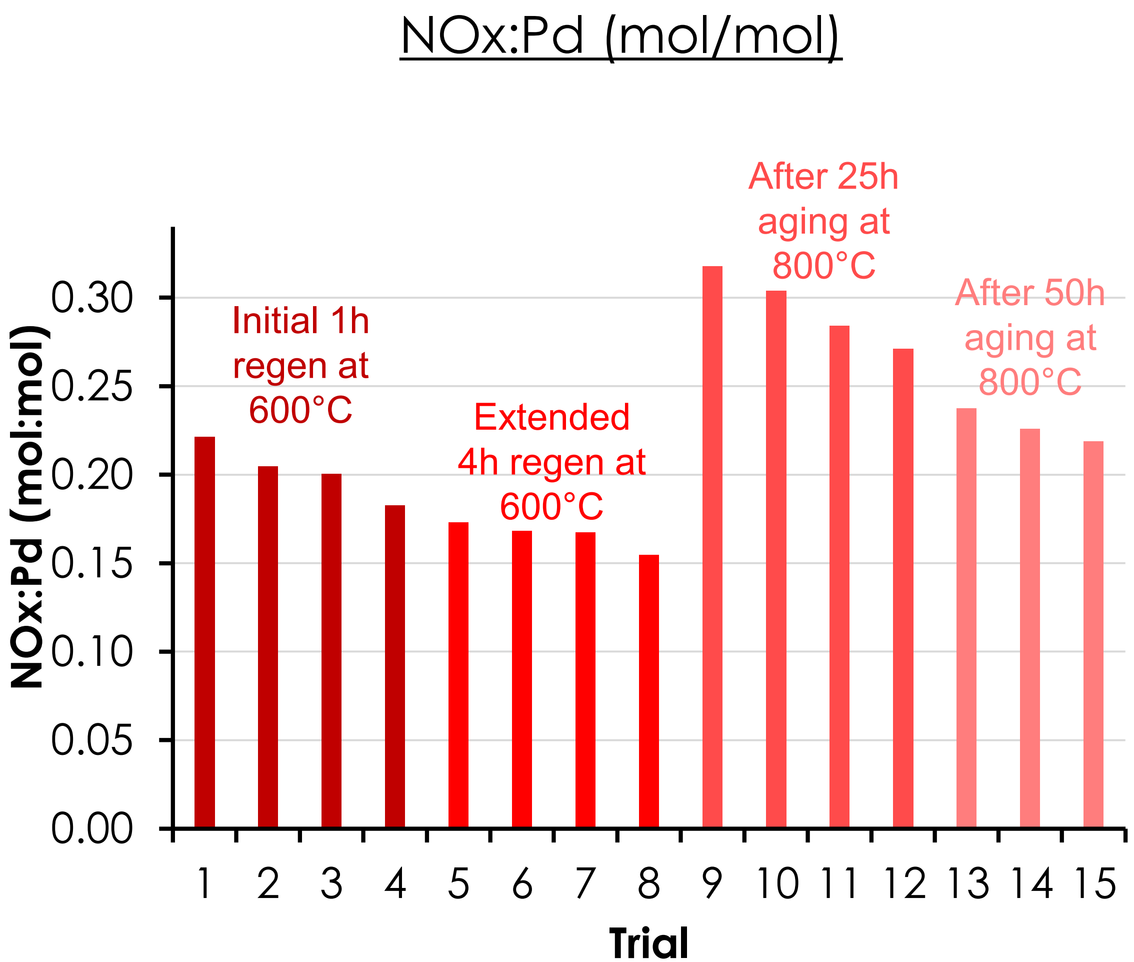
NO:	*100 ppm*
Also H_2, O_2, H_2O and CO_2	

- With continued aging and evaluation NO:Pd continues to decrease
  - 0.24→0.23→0.22 mol:mol
- Suggests loss of Pd ion-exchange sites
  - Goal is to quantify

Tracking NO uptake shows steady decrease

- Evaluation:
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h



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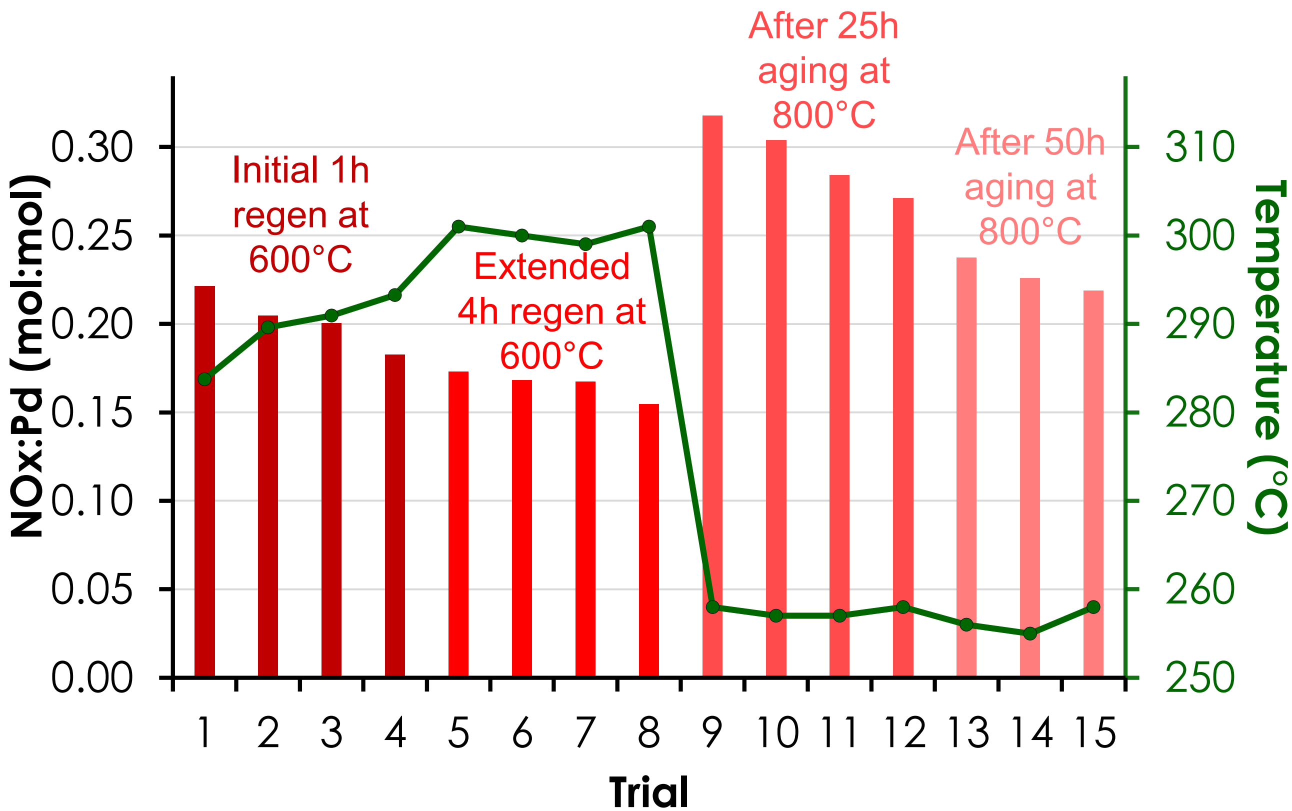
Also H_2, O_2, H_2O and CO_2

Tracking NO uptake shows steady decrease

- Evaluation:
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h

NOx:Pd (mol/mol)



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Also H_2, O_2, H_2O and CO_2

Technical Accomplishments

- Oxidation catalysts
- Trap/Adsorber Materials
  - Hydrocarbon trap
  - Passive NOx adsorbers
- Combined systems

Combining ZSM-5 + Pd/SSZ-13 illustrates stable NO and THC after 4 trials; NO uptake increases

LTC-D oxidation protocol conditions during 30 min storage step at 100°C

total HC_1:	*3000 ppm*
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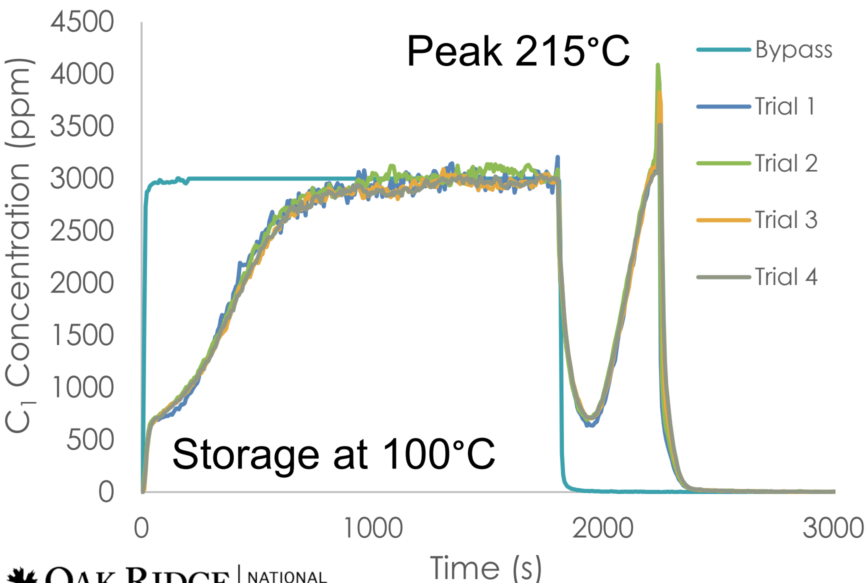
$C_{10}H_{22}$:	*2100 ppm*
CO:	*2000 ppm*
NO:	*100 ppm*

Also H_2, O_2, H_2O and CO_2

- Evaluation:
  - Degreen at 700°C for 15 h
  - 30 min at 100°C → 20°C/min ramp to 600°C → hold 4h
  - Mixture of 100mg ZSM-5 + 100mg 1% Pd/SSZ-13
  - Overall 200 L/g-h including both catalysts (666 sccm)

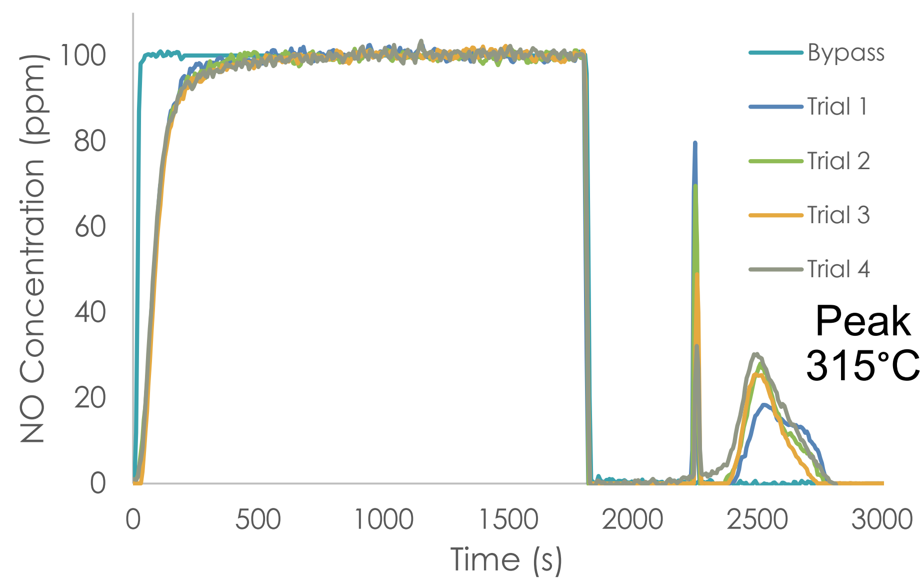
- HC uptake 2.4-2.6 $mmols/g_{cat}$
  - Measured during adsorption

Total Hydrocarbons: FID



- NO:Pd ratio 0.50-0.53 mol:mol
  - Measured during adsorption

Total NOx: chemiluminescence

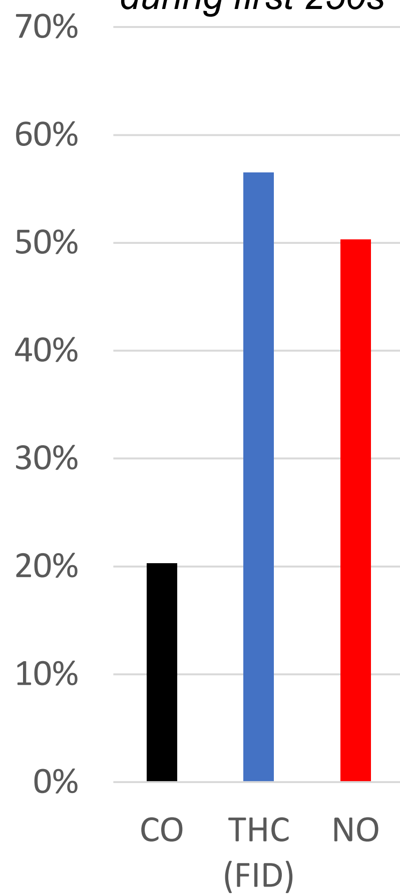


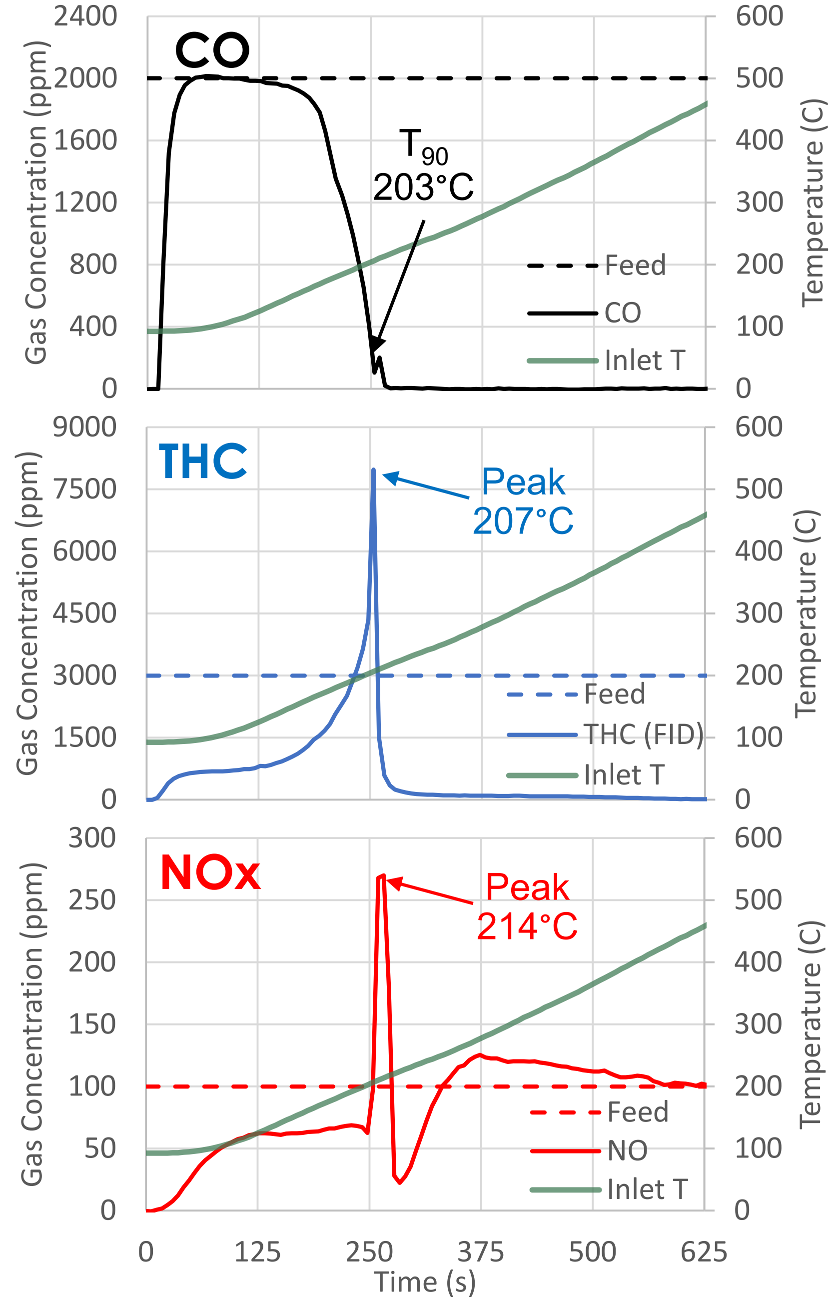
Adding oxidation catalyst shows overall conversion of >50% for THC and NOx

- Evaluation:
  - Introduce reactants and immediately begin ramp
    - 40°C/min ramp to 620°C
  - Physical Mixture of
    - 100 mg ZSM-5
    - 100 mg 1% Pd/SSZ-13
    - 100 mg 0.9% Pt/0.5% Pd/SiO_2@ZrO_2
  - Overall 133 L/g-h including all three catalysts (666 sccm)
- Release of HCs overwhelms oxidation catalyst
  - Need higher activity or more catalyst
- NO:Pd at 250s = 0.68
  - Based on mols in Pd/SSZ-13

Degreened 15h/700°C

*Overall %removal during first 250s**





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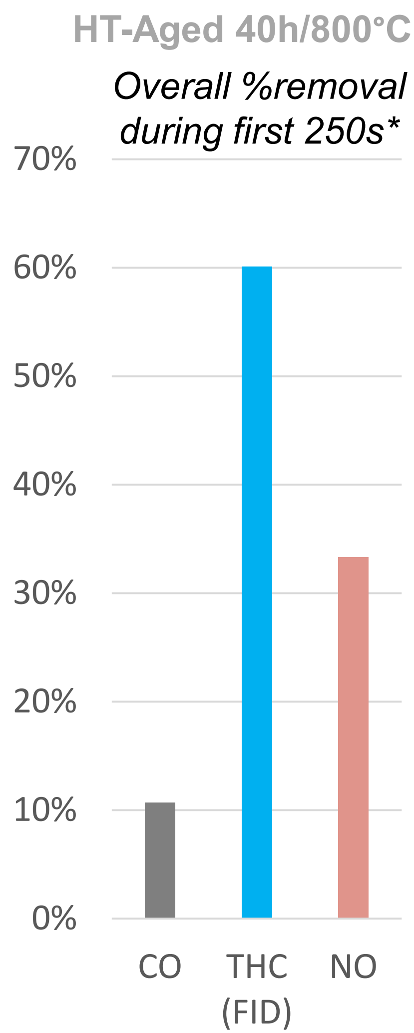
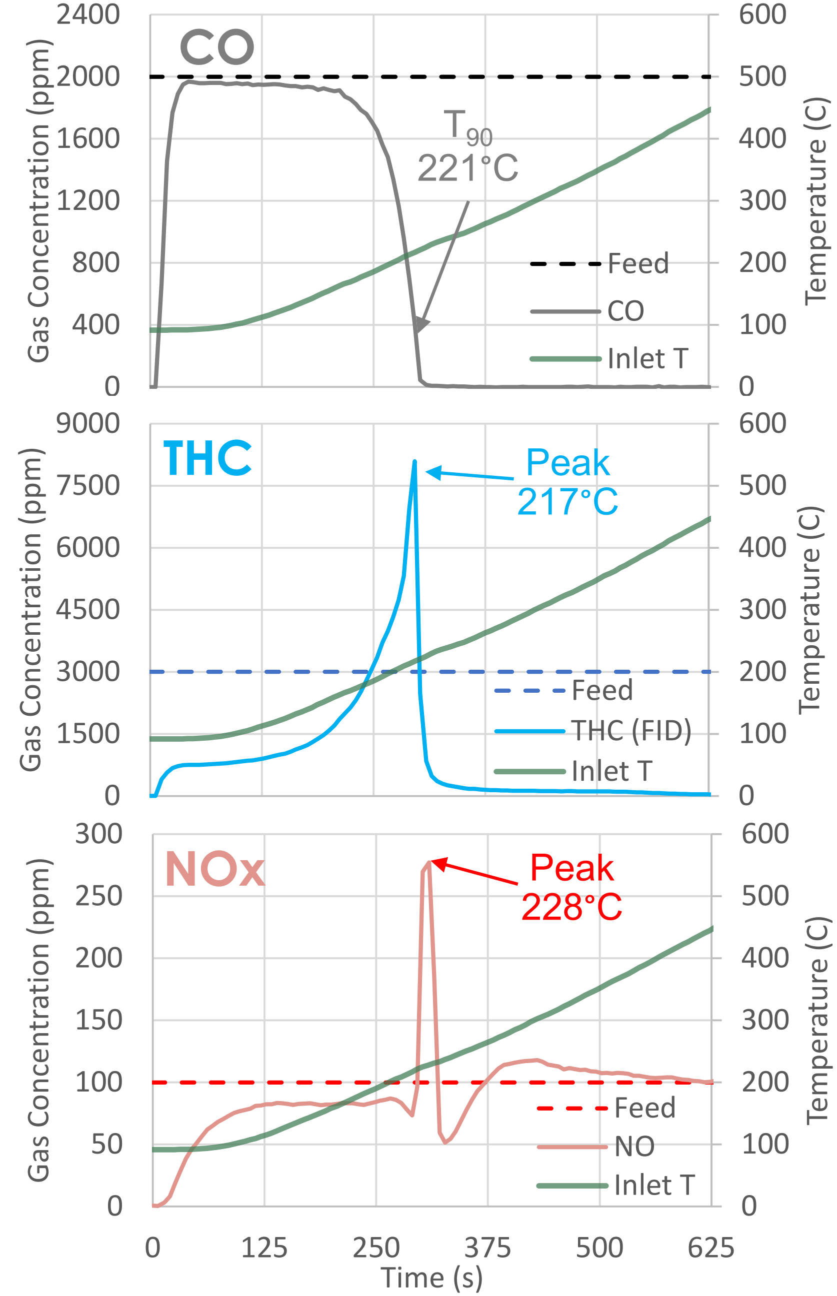
* - Based on Ford study relevant to cold start and time to catalyst lightoff (SAE 2018-01-0938).

Aging 40h at 800°C mostly impacts NO storage; release temperature increases ~15°C

- Evaluation:
  - Introduce reactants and immediately begin ramp
    - 40°C/min ramp to 620°C
  - Physical Mixture of
    - 100 mg ZSM-5
    - 100 mg 1% Pd/CHA
    - 100 mg 0.9% Pt/0.5% Pd/SiO_2@ZrO_2
  - Overall 133 L/g-h including all three catalysts (666 sccm)
- Higher percentage of HCs removed on aged sample
- NO uptake decreases
  - NO:Pd at 250s = 0.38
  - Based on mols in Pd/SSZ-13





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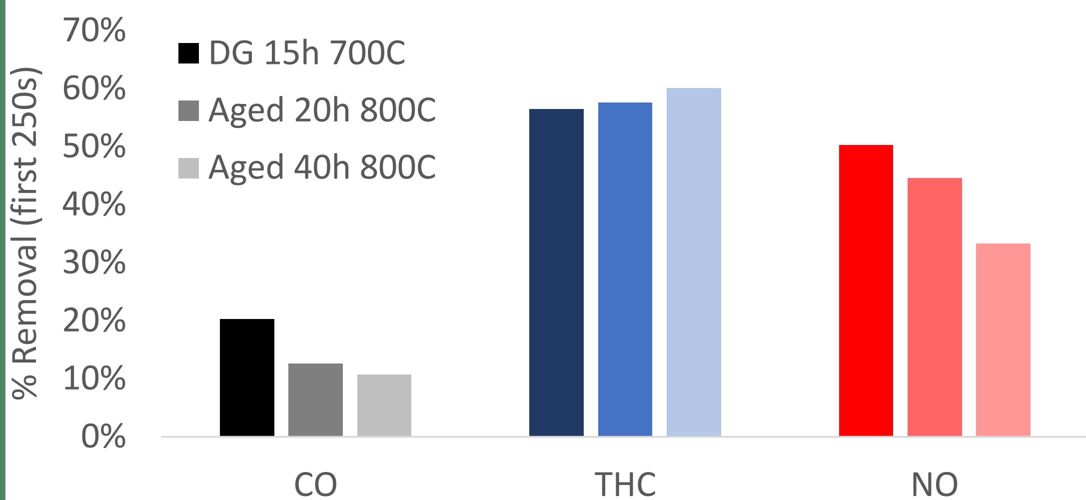
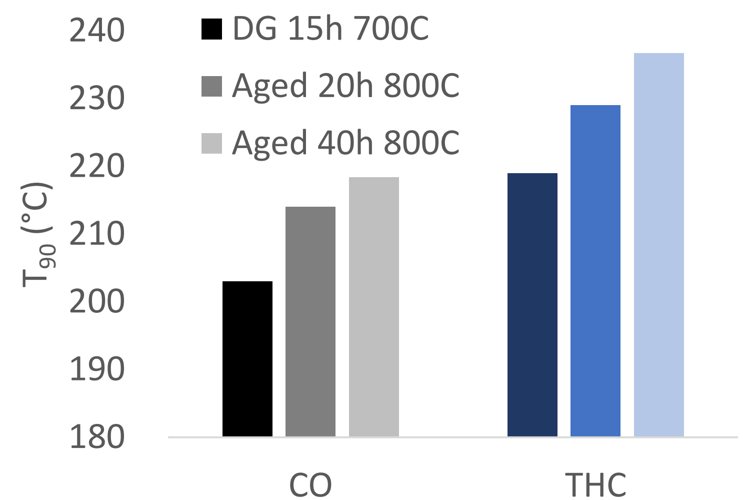
* - Based on Ford study relevant to cold start and time to catalyst lightoff (SAE 2018-01-0938).

Aging 3-component system generally impacts CO and NO functionality more than HC

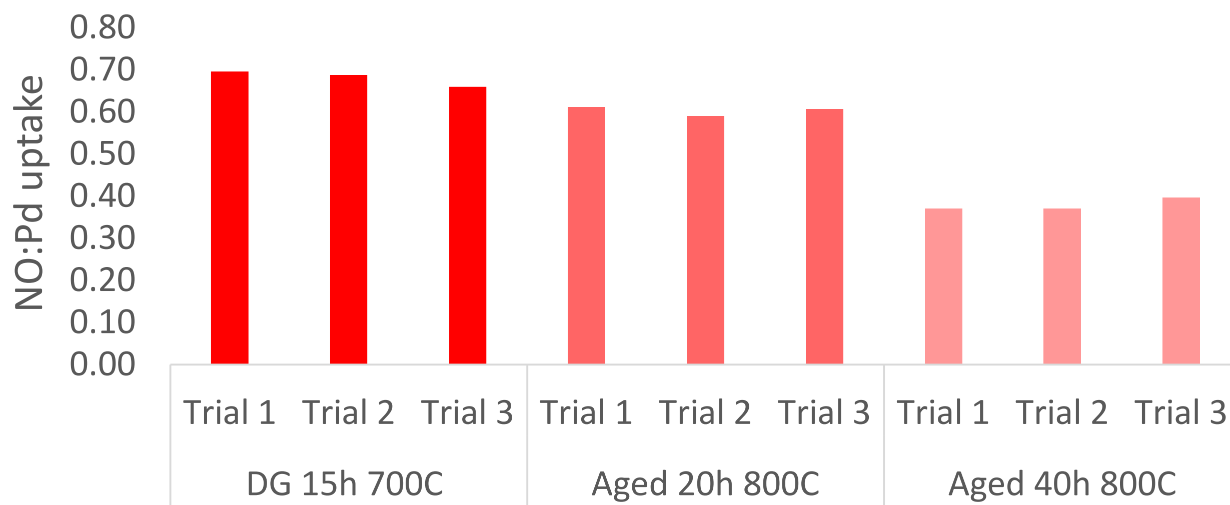
- The percentage removal of CO and NO decreases with aging, but not HC



- Reactivity decreases for both CO and HC



- Unlike in single component system the NO uptake is not decreasing from trial to trial
  - However, thermal aging impacts uptake



Remaining Challenges

Future Directions

- **Oxidation Catalysts**

Need improved oxidation of HCs after aging

Evaluate supports that are already made with emphasis on ceria-based supports*

More characterization to understand strong interaction between support and PGM

Interesting collaboration starting with Harvard University

- **Passive NOx Adsorbers**

NOx uptake is not fast enough

Work with CLEERS to understand what is slowing down uptake and investigate other options

PGM utilization needs improvement under realistic conditions

Introduce surface studies to understand what is limiting access or limiting Pd Ion exchange

- **Hydrocarbon traps**

Increased storage capacity of lighter HCs will be necessary

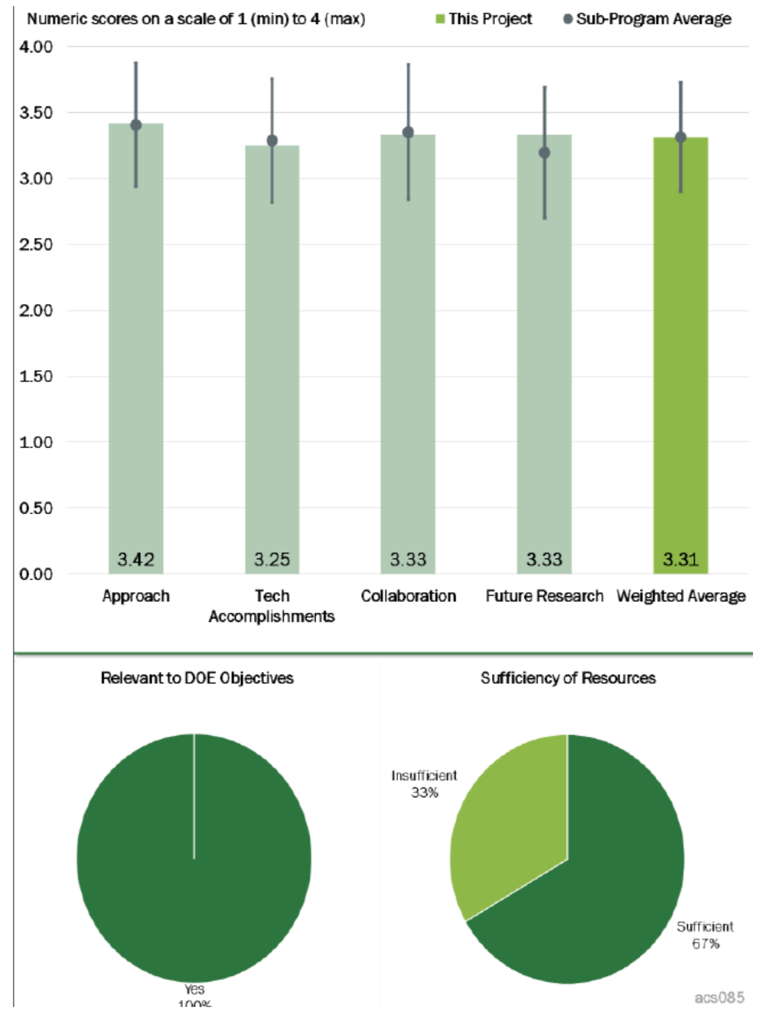
Investigate other zeolites or including non-PGM metals for ion-exchange

* - promising results recently published: Nie et al., Science 358, 1419–1423 (2017).

Any proposed future work is subject to change based on funding levels

Response to reviewer comments

- **REVIEWER: Implement severe aging earlier in the evaluation process**
  - Working to do this as much as possible, but also trying to understand where samples fail in case the aging conditions are not as severe as previously thought
- **REVIEWER: Better understanding of bi-metallics is needed and more characterization is warranted**
  - A specific goal of this years efforts and milestone highlights that; also hired post-doc with specific experience with bi-metallics
- **REVIEWER: Incorporate chabazite into the matrix of samples being evaluated**
  - Successfully procured CHA/SSZ-13 from commercial supplier and exchanged with Pd; large part of the results shown so far and will continue to be so



Summary

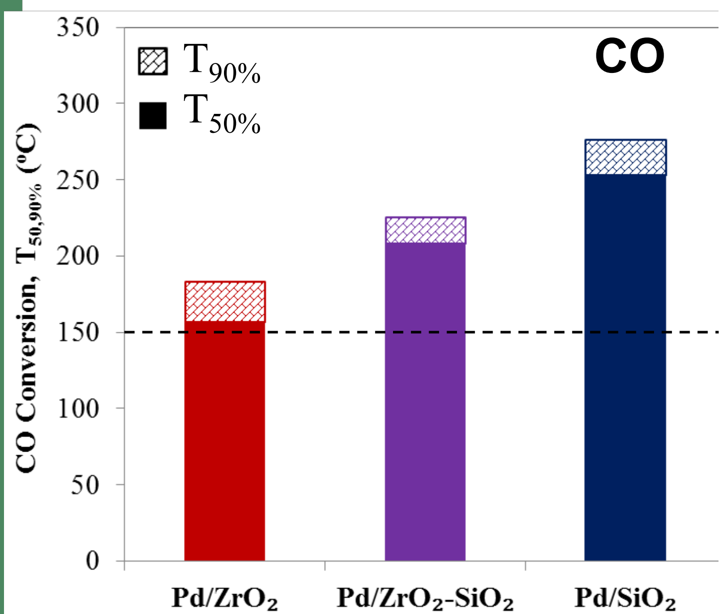
- **Relevance:** Develop new emission control technologies to enable fuel-efficient engines with low exhaust temperatures (<150°C) to meet emission regulations
- **Approach:** employ low temperature protocols to evaluate novel catalysts and systems
- **Collaborations:** Wide-ranging collaboration with industry, academia, other DOE projects, & national labs maximizes breadth of study, guides research from other funding sources
- **Technical Accomplishments:**
  - Synthesized new class of novel supports to be investigated for improved durability and low temperature oxidation
  - Established new collaborations with University at Buffalo and Harvard University
  - Demonstrated HC trap functionality and durability of PGM-free zeolite
  - Evaluated Pd/SSZ-13 for passive NOx adsorption and discovered deactivation mechanism that occurs during evaluation as a single component
  - Demonstrated potential and durability of combining a non-PGM zeolite, Pd/SSZ-13 PNA, and oxidation catalyst to treat low temperature emissions
- **Future Work:**
  - Evaluation of new novel supports aiming to take advantage of the reported activity using ceria supports
  - New collaboration with Harvard investigating high surface area and stable material
  - Develop understanding of Pd ion-exchange with SSZ-13 and losses with evaluation
  - Investigate impact of non-PGM ion-exchanged metals on ZSM-5 and BEA for improved HC trap functionality, especially for smaller molecules

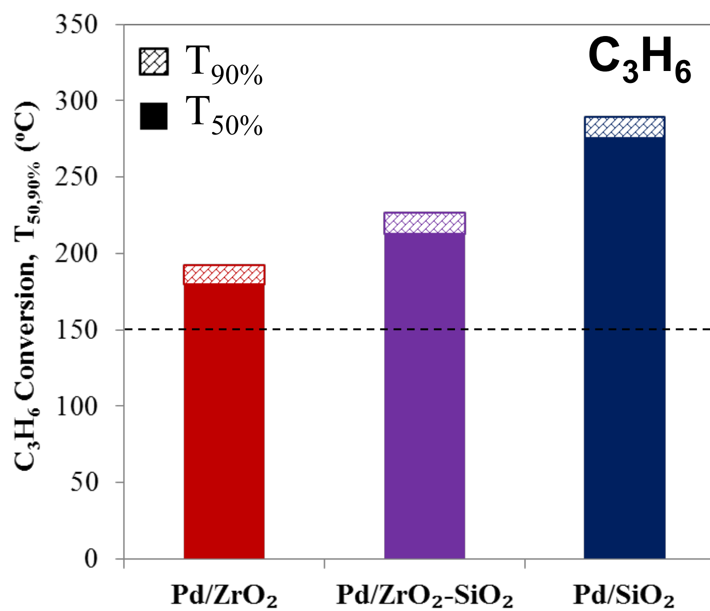
Any proposed future work is subject to change based on funding levels

Technical Backup Slides

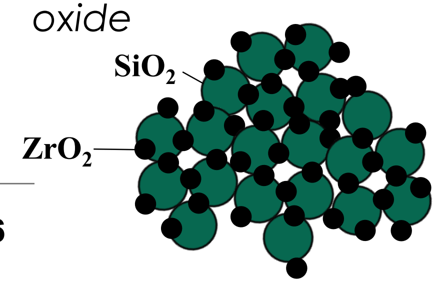
ZrO_2 support has shown excellent activity with Pd catalyst; but looking for improved activity and durability

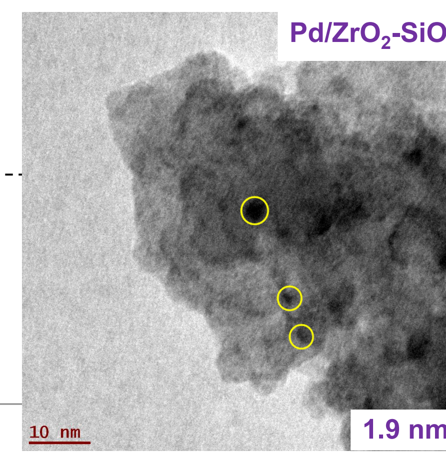
- Pd/ZrO_2 has good activity, excellent thermal durability, good S tolerance
- Goal: further improve activity and sulfur tolerance
  - Support ZrO_2 on high surface area SiO_2
- Initial effort not successful as Pd/ZrO_2 still more active
  - not a monolayer; 15% coverage of SiO_2 surface
  - Pd dispersed on both ZrO_2 and SiO_2





ZrO_2-SiO_2 mixed oxide

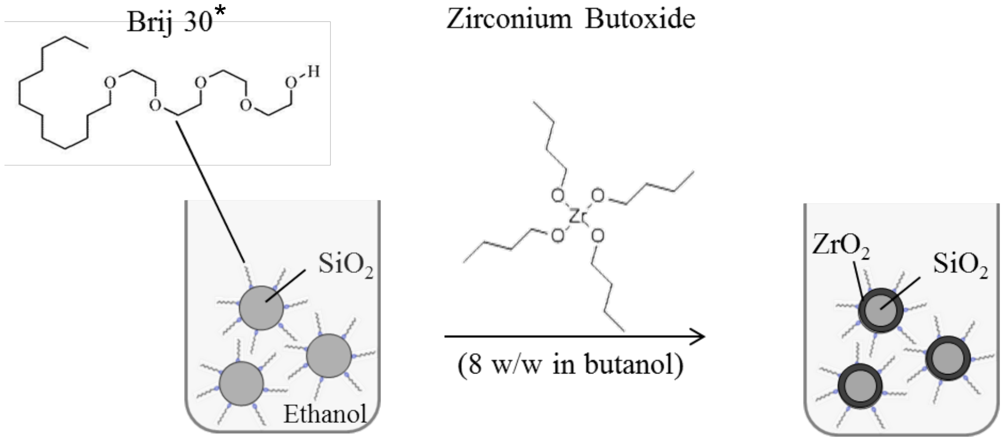




Kim et al. Applied Catalysis B: Environmental 187 (2016) 181–194.

New approach: Cover all of the SiO_2 surface with Zr

Synthesis of SiO_2@ZrO_2 core@shell Oxide Support

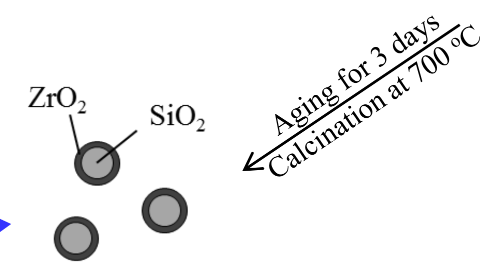


Synthesis of silica spheres

Silica core and amorphous shell with zirconium hydroxide

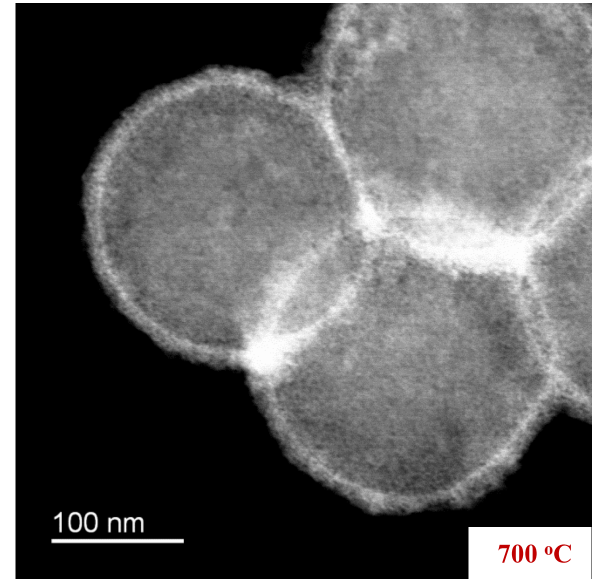
*(Brij 30): Polyoxyethylene(4) lauryl ether

Material	Surface Area (m^2/g)
ZrO_2	97
ZrO_2-SiO_2	153
SiO_2@ZrO_2	**210**

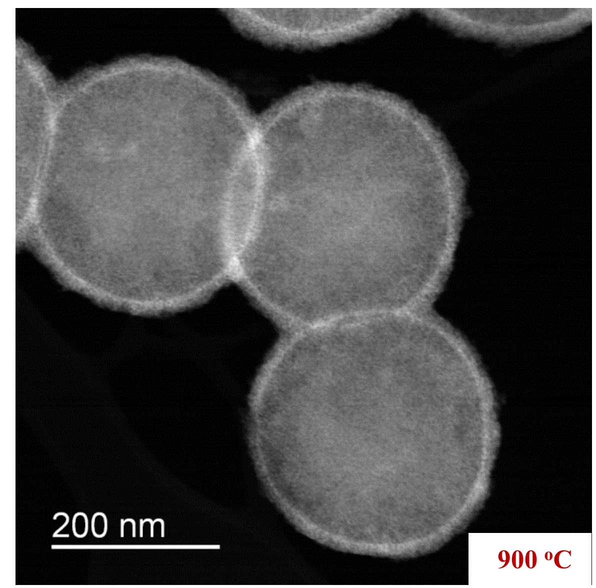


Silica core and zirconium oxide shell after calcination at 700 °C

- **SiO_2** is located in the **core** and **ZrO_2** in the **shell**
- The ZrO_2 **shell** seems to be **porous**
- Growth of SiO_2@ZrO_2 spheres. Shell is maintained. Diameter at: **900 °C: ~250 nm**



700 °C

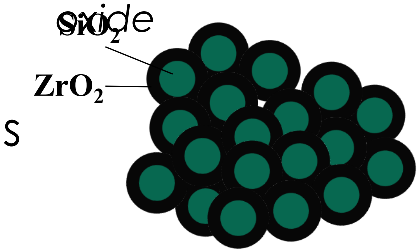


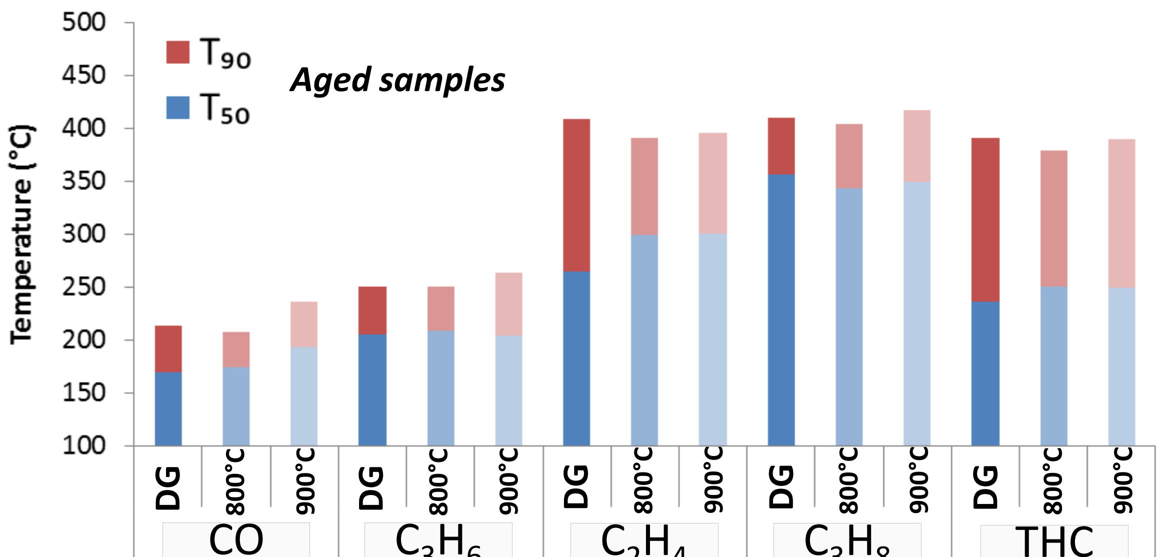
900 °C

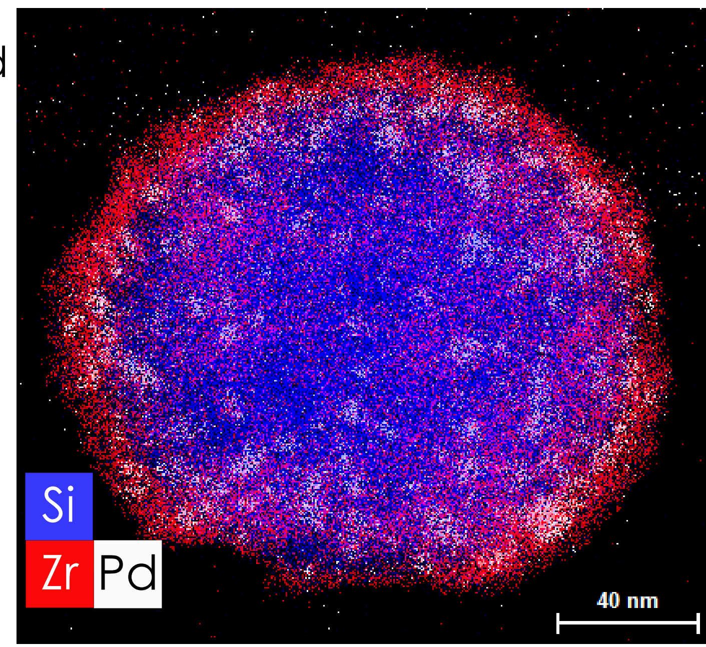
Support: *P.M. Arnal, C. Weidenthaler, F. Schüth, Chem. Mater. 18 (2006) 2733-2739.*

New synthesis technique successfully creates durable ZrO_2 shell around SiO_2 core

- Able to synthesize a complete shell around SiO_2 core using new technique $Pd/SiO_2@ZrO_2$
  - Pd (1 wt%) deposition solely on ZrO_2 outer shell
- While employing US-DRIVE low temperature protocols improved activity shown with this technique
- Robust after aging at 900°C for 10h
  - Improved initial dispersion technique still needed



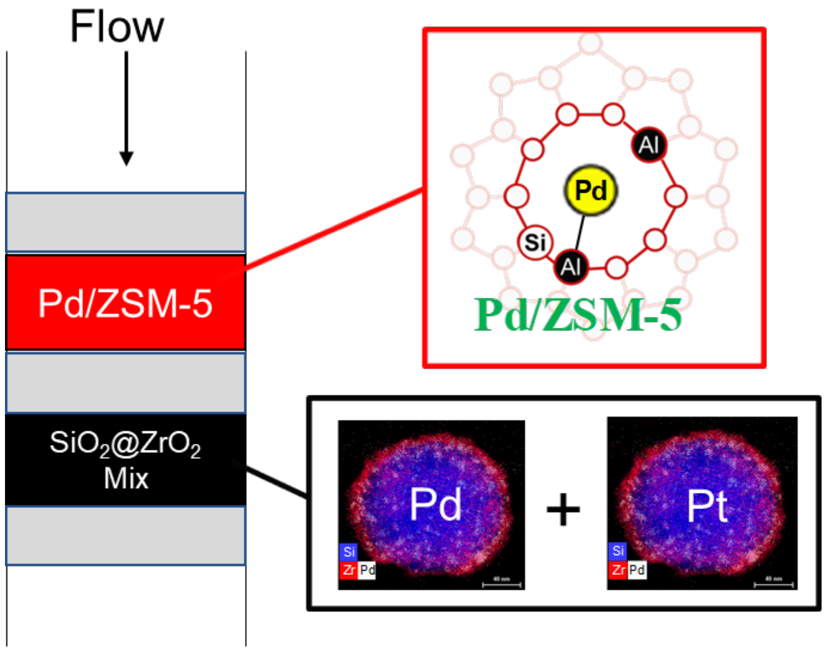


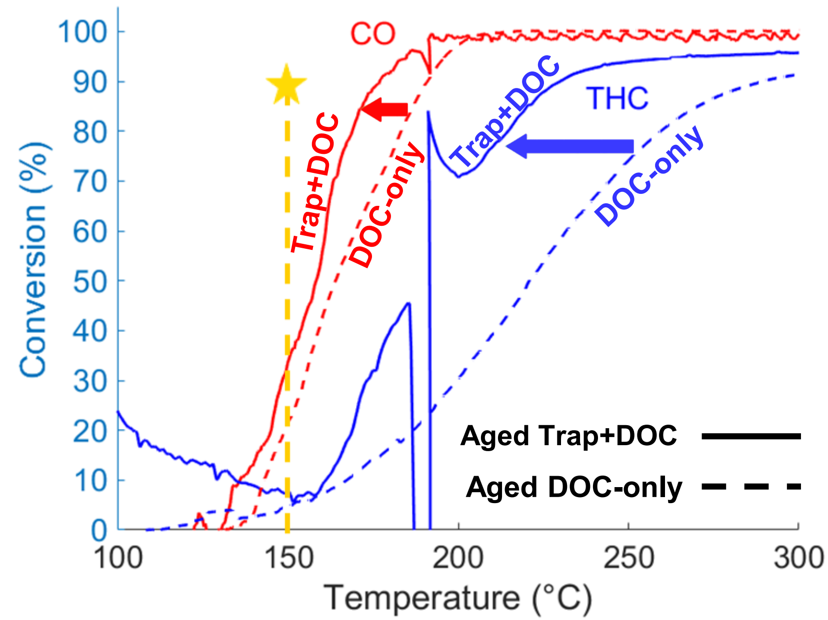


DG = Degreened

This research was performed, in part, using instrumentation (FEI Talos F200X S/TEM) provided by the Department of Energy, Office of Nuclear Energy, Fuel Cycle R&D Program and the Nuclear Science User Facilities.

Trap materials + oxidation catalysts significantly improve overall system functionality after aging





Protocol aging: reaction conditions at 800°C for 50h, 5 ppm SO_2 @ 300ºC 5 h
Desulfation under cycling lean-rich conditions for 30 min at 500ºC, 30s per condition

- Although Pd/ZSM-5 trap is heavily degraded, it still improves reactivity of system considerably in dual-bed configuration

Conditions during 2ºC ramp	
total HC_1:	*3000 ppm*
C_2H_4:	*500 ppm*
C_3H_6:	*300 ppm*
C_3H_8:	*100 ppm*
$C_{10}H_{22}$:	*2100 ppm*
CO:	*2000 ppm*
NO:	*100 ppm*
Also H_2, O_2, H_2O and CO_2	

Pt/CeO_2 is also under consideration and showing remarkable PGM stability

- Simple incipient wetness technique
  - Calcined at 800°C
- Initial surface area is only 37 m^2/g
- 1.4 nm size particles measured after aging
  - CO chemisorption
  - 750 ° C in 10% H_2O for 9h
- Significant room for improvement if dispersing CeO_2 on high surface area support